

White Paper:

Maximizing the Competitive Benefits of Low Cost Natural Gas in the Manufacturing of Carbon Fiber

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Current energy trends shifting towards increased natural gas utilization can result in performance and economic advantages under certain conditions when considered in the design of a Carbon Fiber manufacturing plant. While electricity supply is thought to be more consistent and reliable, it is, in many parts of the world, a more expensive source of energy.

As the industry works towards solutions to develop lower cost carbon fiber, all aspects of the production process are under scrutiny and the consideration of natural gas usage can play an important role in solving the economics puzzle. This paper will discuss innovations to allow for a shift to gas-fired units and hybrid gas / electric designs with improved control and thermal uniformity, as well as a focus on reduction of utilities consumed in the thermal conversion process. Example scenarios will be shown to demonstrate benefits.

Introduction - Universal Plant Concept Explained

Future carbon fiber plants will have to be designed from the ground up to operate at the lowest possible cost. While most of the industry's focus to date has been on reducing overall utility consumption, energy still accounts for 5% to 10% of carbon fiber production's overall costs.[1] In order to achieve the lowest operating costs possible, carbon fiber plants will require the flexibility to utilize either natural gas or electric power, depending on which is cheaper in the given region. Further complicating matters, fluctuating energy markets may cause this preferred energy source to change over time. Thus the ideal universal plant will be of a hybrid design, with the same equipment in a given line able to operate on either natural gas or electricity.

The focus of this hybrid technology will be the oxidation ovens. Of all the unit operations in a carbon fiber line, the oxidation system consumes the most energy by a factor of approximately 4 to 1. This is due to the long fiber residence time and high process atmosphere makeup flow rates, relative to the carbonization steps, required by the Polyacrylonitrile (PAN) oxidation process. Oxidation oven heating accounts for 32% to 40% of the energy used in a carbon fiber line.[2][3] Any reduction in power cost here will translate to a major reduction in the overall operating expense of the carbon fiber line.

Universal Technology and How It Works in Practice

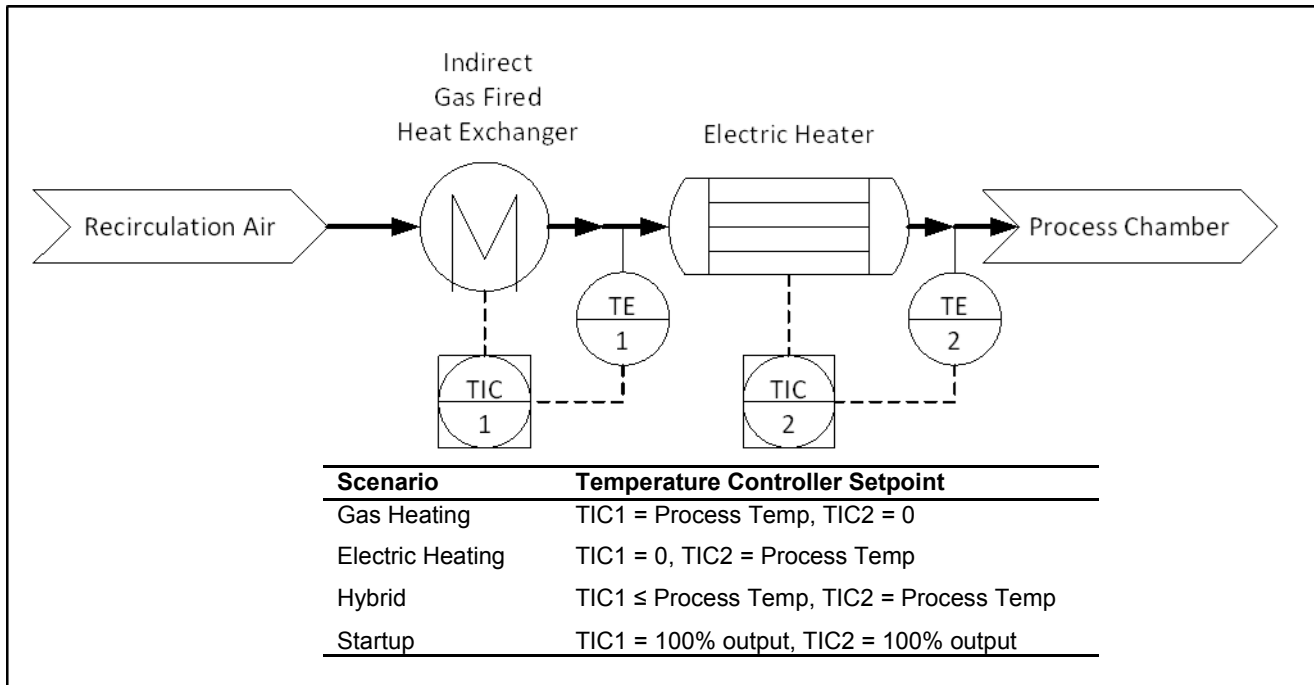
Within oxidation there are typically four to eight thermal zones spread out over two to four large stacks of equipment. Compare this to a carbonization furnace that can have four to ten zones within a single piece of equipment. The ovens are simple, large enough to easily contain redundant heating devices and, given that the oven process consumes ten times as much power as either the low temperature or high temperature carbonization processes (Omnia, LLC, 2012), stand to benefit the most from hybrid heating technology. This all combines to hybrid ovens passing a cost/benefit analysis whereas with a carbonization furnace it is not so obvious.

A typical oxidation oven zone has a recirculation fan blowing air across a set of electric heating elements, raising the temperature of the recirculation air. The power supplied to those heating elements is controlled by a temperature controller that maintains a recipe-specific temperature inside the fiber processing chamber. A hybrid oven would see the addition of an indirect, gas fired heat exchanger in series with the electric elements.

As illustrated in Figure 1, the first temperature controller (gas fired heat exchanger) setpoint would be manually set lower than the second temperature controller (electric elements). That way the first heater would add a set amount of energy, and the second heater would finish the job to bring the recirculating air up to the required process temperature. If no gas is required (electric heating is cheaper) the gas heater would be set to zero and the electric elements would do all the work. If no electricity is required (gas heating is cheaper) the electric heater would be set to zero and the gas would do all the work.

If some combination of heating sources is desired (i.e. electric utility company requests a reduction in consumption during peak summer days) the load could be shared by the two heaters. If the oven is to be heated as fast as possible on startup both heaters can be set to 100% output, achieving much faster heating than either would alone.

Figure 1 – Hybrid Heating Process



Current and Future Trends in Energy Production and Consumption

Overview

The forecast for the energy industry is vastly different today compared to forecasts in recent years. The new dynamics are influenced by an overabundance of supply in the market place partially caused by new supply discoveries as well as an overall reduction in demand. These forces have greatly altered the dynamics of energy in the global marketplace. Capitalizing on these geopolitical paradigm shifts can provide companies with strategic advantages well into the future.

Recent Developments in Natural Gas in North America

Although naturally occurring gas has been known since ancient times, its commercial use is relatively recent. Today, natural gas is a vital component of the world's supply of energy. Natural gas currently supplies more than one-half of the energy consumed by residential and commercial customers, and about 41 percent of the energy used by U.S. industry.[5]

In North America utility markets have experienced a remarkable shift in recent years. The most notable transformation has been the increased production of natural gas deposits in the U.S. Gulf Coast, the Eagle Ford Shale in southern Texas, the Marcellus region in the eastern portion of the U.S. including New York, Pennsylvania, Ohio, West Virginia and a small portion of Virginia, and the Haynesville Shale in Louisiana.

For example, the Marcellus Shale region alone expects to see about 17 pipeline projects meant to ship about 17.3 billion cubic feet per day of natural gas out of Pennsylvania, West Virginia and Ohio to end-users, according to IHS Energy in the next three years.

In North America and elsewhere, these recent discoveries have spurred energy experts and policy makers to focus on natural gas as the main driver to pursue a wide range of goals: easing the impact of energy-price spikes, reducing dependence on foreign oil, lowering greenhouse gas emissions and speeding the transition to renewable fuels.

Natural Gas Rise in North America

According to the Energy Information Administration (EIA), U.S. net imports of natural gas decreased 9% in 2014, continuing an eight-year decline. As U.S. dry natural gas production has reached record highs, lower domestic prices (as shown in Figure 2) have helped to displace natural gas imports. Net natural gas imports (imports minus exports) totaled 1,171 billion cubic feet (Bcf) in 2014, the lowest level since 1987.

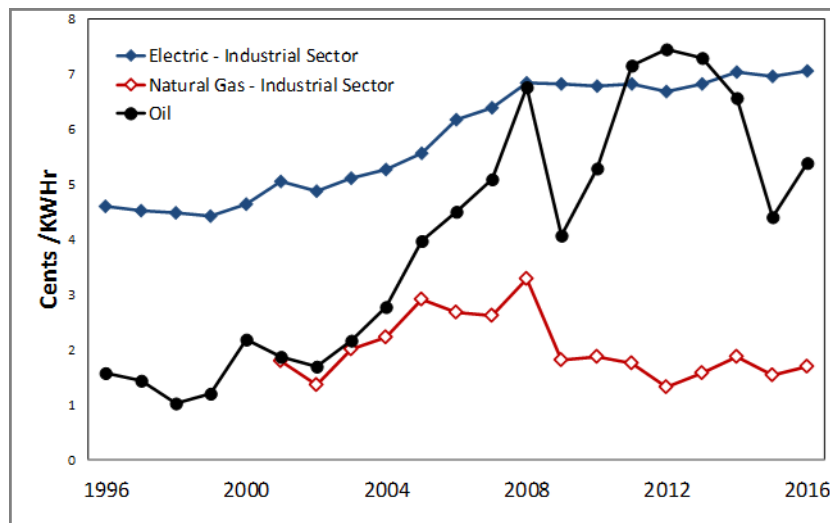
Imports by pipeline from Canada account for nearly 98% of all U.S. natural gas imports, and were the main driver of the decrease in total imports. Net imports from Canada represented 7% of total U.S. natural gas consumption in 2014, down from 11% in 2009.

U.S. natural gas exports also decreased in 2014, but at a slower rate than the decrease in imports, and were still 9% above the previous five-year average. Natural gas exports to Mexico, which account for nearly 50% of U.S. natural gas exports, increased 12% in 2014.

In North America, Crude oil, refined into gasoline or diesel, fuels nearly all U.S. cars or trucks. Coal is the dominant fuel for generating electricity. But as greenhouse gases continue to change our environment, charting a transition to a low-carbon economy will be continue at a breakneck speed in North America and elsewhere. This transformation will fundamentally alter our economy and utility infrastructure as we know it.

Since the market is still largely fragmented and underdeveloped with huge supply reservoirs, a future of uneven development, implementation and new policy implementation will define the marketplace for years to come.

Figure 2 - Energy Pricing in North America by Industrial Sector Pricing ^[6]



Future Energy Infrastructure in North America

In its Annual Energy Outlook 2015,[7] the EIA concludes that dry natural gas production will be the largest contributor to total U.S. energy production through 2040, giving it a 34% share.

In 2013, dry natural gas accounted for 30% of total U.S. energy production, according to the EIA. Coal's share of total U.S. energy production remains slightly above 20% of total U.S. energy production through 2040.

In 2013, coal made up 44% of total generation fuel costs, and natural gas made up 42%. In 2040, coal makes up only 35%, compared with 55% for natural gas. Oil, which is the most expensive fuel for generation, accounted for 6% of the total generating fuel costs in 2013 and from 2019 through 2040 accounts for only 3% of the total. Nuclear fuel accounts for 6% to 8% of electricity generation fuel costs throughout the projection period, according to the EIA outlook.

Natural gas will play a substantial role in North America's energy infrastructure. Figure 3 shows that natural gas production is significantly higher and cost is significantly lower in the United States than the rest of the world. As policy makers in Washington, DC continue its expansion by supporting lucrative investment environmental standards, the industry continues to expand its investments in infrastructure. This will continue the trend of lower gas pricing for industrial users, substantially lower than electric in all categories. As carbon fiber oxidation ovens and low temperature furnace technology are heavy energy users, gas-fired technologies will drive investment decisions well into the future. Harper International leads the way in gas-fired, electric and hybrid oven and furnace technologies.

Figure 3 – World Liquefied Natural Gas Estimated November 2013 Landed and Hub Prices \$US/mmbtu[8]

Production (bcm)		
	2008	2035
Russia	662	881
Iran	130	279
Turkmenistan	71	136
Canada	175	192
United States	575	779
Norway	102	127
Australia	45	155
Qatar	78	260
Indonesia	74	119
Nigeria	32	119
Algeria	82	168
Latin America Total	148	292



Reserves (bcm)	
Mozambique	2825
Tanzania	565
Israel	407

Theoretical Case Study

Effects of Hybrid Oxidation Technology on Operating Expense

In this section we will consider a theoretical analysis of three carbon fiber lines and the impact of different oxidation energy sources on operating expense (OpEx).

- Line 1 – 3 meter – Current industry standard production scale
- Line 2 – 4 meter – Upcoming production scale
- Line 3 – 5 meter – Future production scale

We will look at two different way of powering these lines.

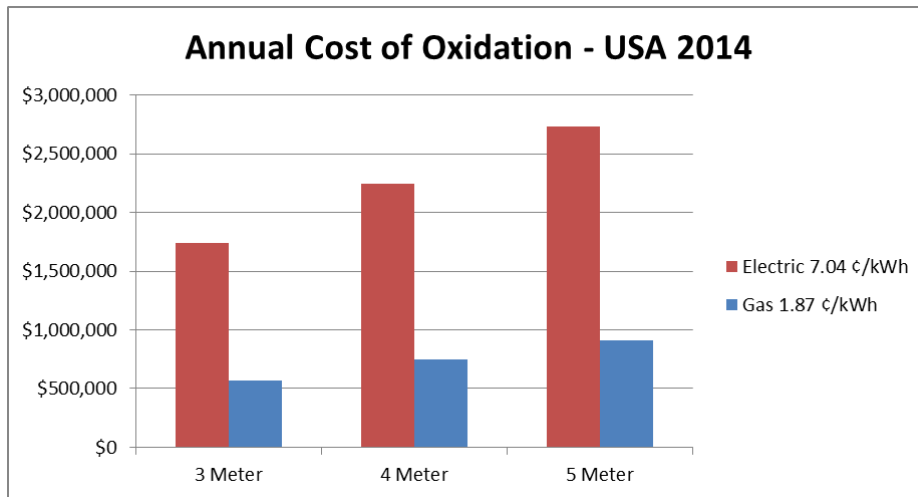
- Scenario 1 – Electric Oxidation
- Scenario 2 – Gas Oxidation

Table 1 - Major Assumptions Used for Calculations

Line Size	Tow Type	Line Speed	Tow Count	Production Capacity (Tons/Year)	Electricity Cost	Natural Gas Cost
3 Meter	48k	10 m/min	130	2007	7.04 ¢/kWh	1.87 ¢/kWh
4 Meter			174	2686		
5 Meter			217	3349		

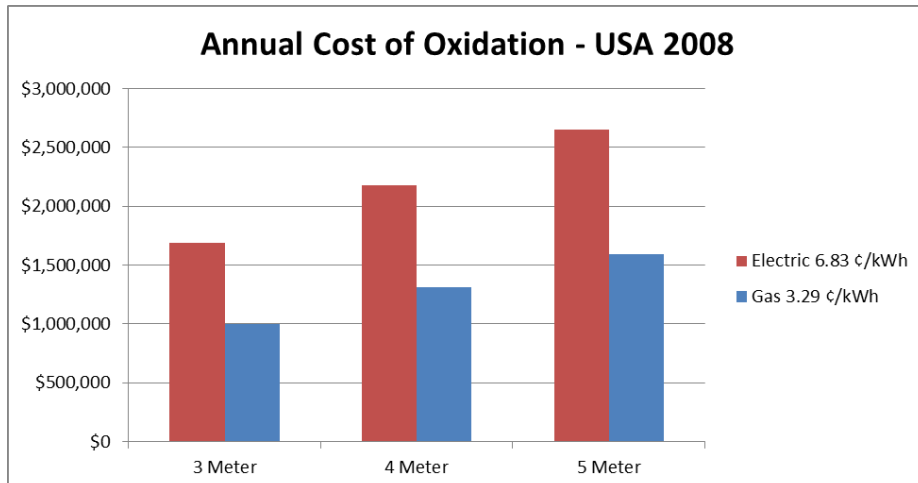
These process parameters were used as inputs to Harper's standard process models to predict expected energy consumed by heating the oxidation systems in our three lines. These energy consumption values were in turn multiplied by Industrial Sector costs of both gas and electricity obtained from the US Energy Information Administration's Short Term Energy Outlook.[9] Results are shown in Figure 4.

Figure 4 – Calculated Annual Cost of Oxidation, 2014



The advantage of natural gas isn't always so great. 6 years earlier costs were as shown in Figure 5.

Figure 5 – Calculated Annual Cost of Oxidation, 2008



In other parts of the world natural gas and electric heating are much closer in cost. There are even times, such as off peak times when demand on the electric grid is low, when it is actually cheaper to heat the oxidation ovens with electricity than with natural gas.

Effects of Gas Fired Low Temperature Carbonization on Operating Expense

To demonstrate the complexity of the problem, we will now consider the effect of choosing a gas or electric low temperature (LT) carbonization furnace. As process temperature increases, the efficiency of gas heating decreases.[10] A fairly typical zone count and temperature profile was assumed when modeling electricity and gas energy consumption. Figure 6 shows the resulting cost to heat the LT furnace at 2014 utility costs. Figure 7 shows the results of the same calculations, but using 2008 utility costs.

Table 2 – LT Zone Temperatures and Natural Gas Efficiencies

Zone	Temperature Setpoint (°C)	% Available Heat (Assume 50% Excess Air)
1	400	72
2	450	68
3	500	66
4	600	58
5	700	53
6	750	49
7	700	53

Table 3 –Resulting Energy Consumption Predictions

	3 Meter	4 Meter	5 Meter
LT - Electric (kW)	297	387	476
<i>or</i>			
LT - Natural Gas (m3/hr)	66	87	106

Figure 6 – Calculated Annual Cost of Low Temperature Carbonization, 2014

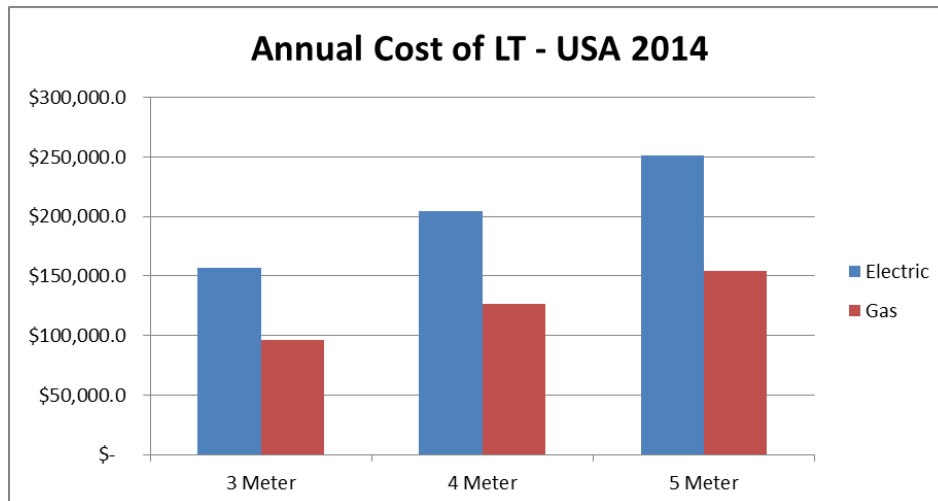
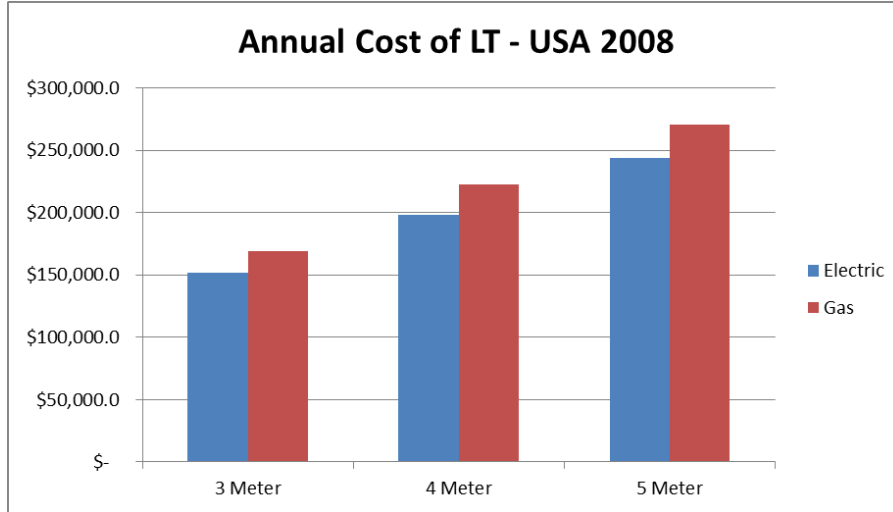


Figure 7 – Calculated Annual Cost of Low Temperature Carbonization, 2008



In 2008 it would have been cheaper to heat a Low Temperature carbonization furnace with electricity than with natural gas. This year was an anomaly, with market forces temporarily inflating the cost of natural gas in the United States. The purpose of this analysis is that even in regions such as the United States, where natural gas is usually lower in cost than electricity, the choice is not always obvious. Here the heating source preference would be as follows:

- Good – Electric Ovens, Gas LT
- Better – Gas Ovens, Gas LT
- Best – Hybrid Ovens, Gas LT

This good/better/best scenario of gas versus electric heating applies to regions where natural gas is consistently the lower cost energy source. In other parts of the world it may be different. Thus, a hybrid plant design is universally optimal.

Other Considerations

Reliability

In a hybrid oxidation system, the redundant heating sources would lead to greater reliability. The electric heating elements and gas fired heat exchangers would both be sized for the full heating load in order to accommodate either entirely electric or entirely gas heating. Thus simple reliability through redundancy would be achieved. If a heating source fails, the other would be able to maintain operation until the end of the campaign when the faulty unit can be replaced.

Daily Operation

Electric utility companies often structure their customer contracts so that there are expensive penalties for high consumption during peak demand times, such as mid-day in the summer months. To avoid this, plants that can scale back effectively often reduce their production during these times. For example, it is common practice for industrial gas plants to reduce the output of their cryogenic air separation units during mid-day hours in the summer.

This is not an option for carbon fiber lines where a reduction in output during a campaign, such as slowing the line speed, would change the time/temperature recipe and thus ruin the product fiber. The only way to reduce electricity consumption during a campaign would be to divert some of the load to a secondary heating method (natural gas) during the peak hours.

High Temperature and Ultra High Temperature Furnaces

The last thermal processing steps in a carbon fiber line, high temperature (HT) and ultra high temperature (UHT), are not discussed here. These processes operate between 1200°C and 2800°C. The efficiency of natural gas decreases as processing temperature increases. Thus natural gas usually makes sense for the oxidation ovens (250°C), and can make sense for the LT Furnace (800°C), but is never a viable option for the HT and UHT furnaces. Electric heating is the preferred technology in these processes.

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